THE PRODUCTION OF SCIENTIFIC KNOWLEDGE.[1]

THE increase of scientific knowledge can be divided into three steps: first, the production of new knowledge by means of laboratory research; secondly, the publication of this knowledge in the form of papers and abstracts of papers; thirdly, the digestion of the new knowledge and its absorption into the general mass of information by critical comparison with other experiments on the same or similar subjects. The whole process, in fact, may be likened to the process of thought. We have first the perception by means of the senses. The percept is then stored in the memory, and in the mind is compared with other previously stored percepts, and finally forms with them a conception.

I desire in this paper to consider the methods by which these three sections of the production of knowledge may be carried on, to suggest an arrangement of laboratories to produce experimental results dealing with any branch of science, then to consider how the knowledge so obtained may best be stored and classified, and, finally, the methods to be employed to make the results of scientific research available for application.

(1) *Research Work.*

The agencies engaged in scientific research are of several kinds. The traditional home of research work is in the university, and the bulk of the scientific production of the world comes from institutions connected with teaching. The industries are more and more supporting research laboratories, a large number of which contribute to the general fund of scientific knowledge by publishing the results which they obtain, and some of which are engaged upon purely scientific work of no mean order. Consulting and technical laboratories engaged in industrial work make frequent contributions to science, and there are some very important laboratories engaged in pure research work which are supported by philanthropic foundations.

The classification of research laboratories is not altogether an easy task. They may obviously be classified according to the source of the funds which support them—that is, we may classify them as university laboratories, industrial laboratories, Government laboratories, institution laboratories, and so on—but if we look at them simply in the light of the research undertaken, this does not seem to be altogether a logical classification, since there is little distinction between the work done in some university laboratories and some industrial laboratories, and the work of the Government and institution laboratories again overlaps that of the two former classes.

The University of Pittsburg, for instance, has an industrial laboratory, where definitely technical problems are dealt with. The research work on photometry done at Nela Park and at Cornell University would seem to be similar in kind, and work on physical chemistry or on the structure of chemical compounds is of the same type, requires the same class of workers, and produces the same results, whether it be done in a university, in a laboratory of the Carnegie Institution, or in such an industrial laboratory as that of the General Electric Co. It is equally difficult to classify laboratories according to the purpose for which researches are avowedly carried on. Most university laboratories are willing to undertake work of industrial value, and, indeed, some specialise in such problems, while many industrial laboratories are quite willing to carry out a research of purely academic and theoretical interest provided the problems involved bear a relation to the general work of the laboratory.

A useful classification of laboratories can, however, be obtained if we consider whether the problems investigated in a laboratory are all connected with one common subject or whether the problems are of many kinds, having no connecting bond of interest. I would suggest that the first type of laboratory might be called "convergent" laboratories, and the second "divergent."

In the "divergent" group of laboratories are included all those institutions where research is carried on which are interested in science in general or in science as applied to industry, and will attack any problem that may seem to promise progress in knowledge or, in the case of an industrial laboratory, financial return. Most university laboratories are of this type. When they devote themselves to special problems it is usually because of the predilection of some professor, and as a general rule a student or instructor may choose any problem in the whole field of the science in which he is working and may carry out an investigation on that problem if he be interested in it without regard to the relation of his work to the other work which is carried on in the same laboratory.

Correspondingly, in most industrial laboratories the problems investigated are those which present themselves as a result of factory experiences or of suggestions from the men working in the laboratory, and promise financial return, and the different problems carried on in the same laboratory are not necessarily related in any way whatever.

The greater number of university and industrial laboratories are necessarily of this type. It would be a disadvantage for a university laboratory, the primary business of which is training students, to be too narrowly specialised. Specialised university laboratories are desirable only in the case of post-graduate students, and it would be very inadvisable to allow the laboratories responsible for the general training of scientific men to specialise in one branch of science, since as a result the students would acquire a proper acquaintance with only a limited portion of their subject.

Industrial laboratories, on the other hand, must necessarily be prepared to deal with any problems presented by the works, and as these will be of all kinds, covering generally the whole field of physics, chemistry, and engineering, it is impossible for the usual works laboratory to specialise except in so far as it deals with the works processes themselves.

In the "convergent" laboratories, however, although the actual investigations may cover as great a range of science as those undertaken in a "divergent" laboratory, yet all those investigations are directed towards a common end—that is, towards the elucidation of associated problems related to one subject. Thus, the staff of the Geophysical Laboratory, which includes physicists, geologists, crystallographers, mineralogists, and chemists, works on the structure of the rocks, and although the field of the actual investigations ranges from high-temperature photometry to the physical chemistry of the phase rule, yet the results of all the work carried out are converged on the problem of the structure of the earth's crust.

The Nela Park Laboratory, in the same way, is studying the production, distribution, and measurement of illumination, and all its work, which may involve physiology, physics, and chemistry, is related to that one subject. Such convergent laboratories sometimes develop in universities owing to the intense interest of a professor in a single subject and to the enthusiasm which inspires students and assistants to collaborate with him and to concentrate all their energies on the same group of problems. There are many examples of such laboratories, such as the laboratories dealing with radio-activity, and those which are concerned chiefly with spectroscopy. Among others may be mentioned the Cavendish Laboratory at Cambridge and several of the larger university laboratories which deal with the physical chemistry of solutions.

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[1] From a paper read before the Rochester Section of the Optical Society of America on October 23, by Dr. C. E. Kenneth Mees.

But these university laboratories are rarely able to concentrate on to the group of problems which they are studying specialists from such different branches of science as are available for similar laboratories outside the universities owing to the fact that it is very difficult to obtain interdepartmental co-operation in research in a university. In a specialised laboratory, on the other hand, workers in all branches of science may well collaborate in the investigation of problems representing different points of view of one general subject.

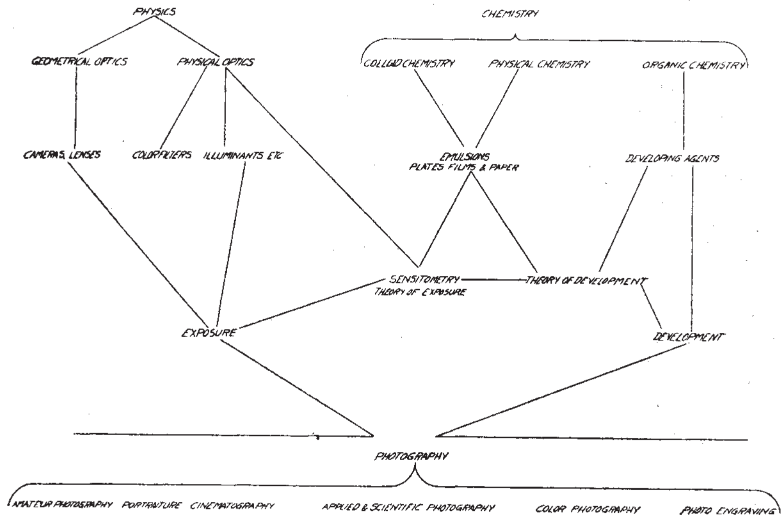

FIG. 1.

In addition to the examples of industrial and institutional laboratories mentioned above I should like to illustrate the structure of a convergent laboratory, if I may be forgiven for doing so, by referring to the organisation of the research laboratory with which I am connected—that of the Eastman Kodak Co.

The purpose of this laboratory is the investigation of the scientific foundations of photography and its applications, everything relating to photography in all its branches and applications being of interest. The branches of science which are of chief importance in photographic problems are those of optics in physics and of the colloidal, physical, and organic branches of chemistry, and the relations of these sciences to photographic problems are shown in graphic form in Fig. 1.

Optics deals on its geometrical side with the materials used in photography—cameras, lenses, shutters, etc.—and on its physical side with such materials as colour filters and illuminants, but especially with the study of the relation of the photographic image to the light by means of which it was produced—a study which is known by the name of sensitometry. The manufacture of the sensitive material itself, which on modern photographic plates, films, and paper is called the emulsion, is a province of colloid and physical chemistry, colloid chemistry dealing with the precipitation and nature of the sensitive silver salts formed in their gelatine layer, while physical chemistry informs us as to the nature of the reactions which go on, both in the formation of the sensitive substance and in its subsequent development after exposure.

The organic chemist prepares the reducing agents required for development and the dyes by which colour sensitiveness is given to the photographic materials and by which the art of colour photography can be carried on, and while the physicist therefore deals with sensitometry and the theory of exposure, the chemist must deal at the same time with the theory of development and with the conditions relating to the development of photographic images.

A laboratory, therefore, for the study of photographic problems must be arranged with a number of sections, such as are shown in Fig. 2. In physics we require departments dealing with sensitometry and with illumination, reflection and absorption, colorimetry, spectroscopy, and geometrical optics. We need a department of colloid chemistry, one of physical chemistry, one of organic chemistry, one of photo-chemistry to deal with the action of light upon the plate, and, finally, a number of photographic departments dealing with photographic chemistry, with portraiture, colour photography, photo-engraving, motion-picture work, and X-ray work, and all these departments are converged together first upon the theory, and then upon the practice, of photography.

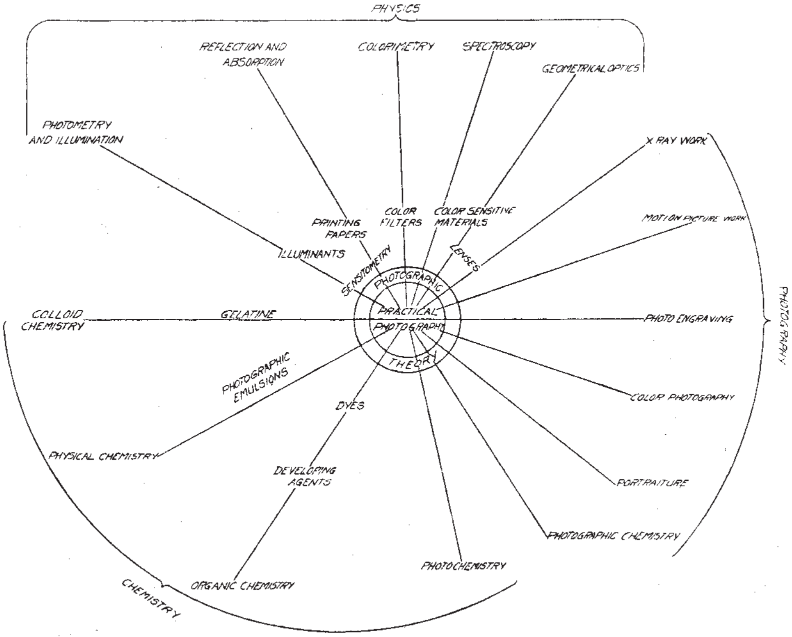

FIG. 2.

Each research specialist in the laboratory is given work corresponding with a limited field of science, so that while his special attention is devoted to that one department his field of activity just overlaps that of the departments on each side of him, while his general knowledge of the subject should, of course, cover a much wider range. It is important that each man should have his own special field of work, and that overlapping should not be complete, since such complete overlapping will inevitably produce friction destructive of co-operation and harmony. The way in which such a subdivision is arranged may perhaps be best illustrated by Fig. 3, which shows the range of the specific investigations of those who in our laboratory cover the range of research work between sensitometry and pure physical chemistry. There are five workers in this range; the first, A, being a pure physicist, B a physicist with a considerable experience of chemistry, C a physical chemist who is specialised in photography, D a physical chemist who is specialised in photographic theory, and E a pure physical chemist. The interest of each of these workers overlaps the field of the other workers, but nevertheless each of them has his own specific problem, his own equipment and apparatus. Thus, A and B use sensitometric apparatus chiefly, C both sensitometric apparatus and the thermostatic and electrical equipment of physical chemistry, D microscopic apparatus and chemical apparatus dealing with the precipitation of silver salts, and E the analytical and solubility apparatus of chemistry.

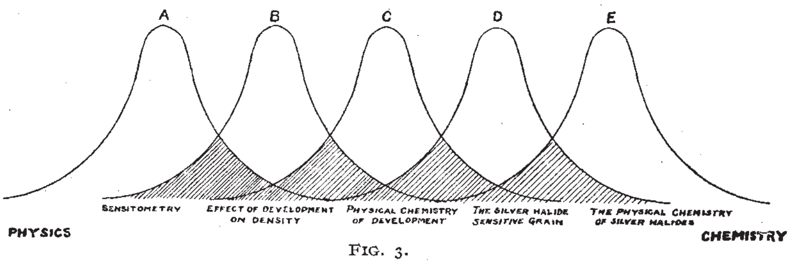
A
B
C
D
E
SENSITOMETRY
EFFECT OF DEVELOPMENT ON DENSITY
PHYSICAL CHEMISTRY OF DEVELOPMENT
THE SILVER HALIDE SENSITIVE GRAIN
THE PHYSICAL CHEMISTRY OF SILVER HALIDES
PHYSICS
CHEMISTRY

FIG. 3.

The whole of this range is also connected with colloid chemistry, and especially the overlap of the different sections involves colloid problems, so that we can consider colloid chemistry as dealing with the interrelations of the different sections of photographic chemistry, and can represent its province in the diagram by shading the overlapping areas. The colloid division of the laboratory will therefore be interested in the work of each of the specific investigators, and will be of assistance to all of them.

These charts, prepared for a photographic laboratory, are equally applicable in form for almost any other convergent laboratory, so that if we have to work out the organisation of a research laboratory which is to study any interrelated group of problems, we can do it by the construction of charts similar to these. Thus, considering Fig. 1, we place first at the bottom of the chart the general subject considered and its various branches, and then above these the scientific problems involved, separating out on opposite sides of the chart those problems which would involve different branches of pure science. Thus, we can place on one side biological problems, then physical problems, then chemical problems, and so on, so reconstructing a chart similar to Fig. 1 from the bottom up, until at the top we have the various branches of pure science involved, subdividing these branches until each subdivision represents the work capable of being handled by one man in the laboratory.

It will now be possible to draw Fig. 2, showing on the circumference the different sections of the laboratory for which accommodation, apparatus, and men must be provided, and showing the relation of these sections to the problem as a whole, and having worked this out, it is easy to find the amount of space and the number of men which will be required or which the funds available will allow for each part of the work.

Specialised laboratories may originate in various ways, but it seems clear that with an increasing total amount of research and with an increasing realisation of the importance of research more laboratories will be developed, and no doubt laboratories which originally were of the divergent type will with their growth tend to split into a linked group of convergent laboratories. Consider, for instance, a very large industrial research laboratory covering a wide field of research and dealing with many different types of problems. There are two types of organisation possible to such a laboratory. It might be divided according to the branches of science in which the workers were proficient. It might have, for instance, chemical divisions, physical divisions, and so on, but if the groups of problems dealt with were reasonably permanent in their character it would more probably develop into a group of convergent laboratories in which men from different branches of science—chemists, physicists, and so on—worked together (and probably even had their working places in proximity) because they were working on the same general problem. Any national laboratory which is developed for industrial research, for instance, should almost certainly be organised as a group of convergent laboratories rather than as a group of separate physical, chemical, engineering, etc., laboratories.

We may expect, then, that the general organisation of scientific research will tend towards the production of numbers of specialised laboratories, each of which will be working on an interrelated group of problems, and attacking it from various points of view.

Some of the questions relating to the internal organisation suitable for these convergent laboratories have already been discussed in a former paper,[2] and I need only add here that the "conference" system described there as a method of actually carrying on the scientific work of the research laboratory has continued to prove quite satisfactory.

(2) *The Classification of Scientific Knowledge.*

The work of the research laboratories is published by various methods in the form of scientific papers, and with the increasing amount of research done the number of technical journals is increasing steadily, so that the workers in most branches of science find it difficult to keep up adequately with the current literature, and especially those who become interested in the light thrown upon their own problem by other branches of science find it a task of great magnitude to acquaint themselves adequately with the literature. In order to meet this difficulty the various scientific societies publish journals giving abstracts in a conveniently indexed form of all the important papers published, and these abstract journals are of great value in searching for information on special subjects.

In spite of these abstract journals the task of obtaining all the references to the literature on a given subject is still a formidable one, and might be very much simplified by the adoption of some radical changes in the organisation of the abstraction and classification of scientific knowledge. In the first place, there seems to be no reason why abstracts of scientific papers should be prepared by the national societies. At present, for instance, there are at least four complete sets of abstracts of chemical papers prepared in different countries, together with a number of less complete sets, and this represents a great overlapping and duplication of effort. Secondly, sciences which have not so many or such wealthy workers as chemistry cannot afford to produce any complete abstract journals, so that in these sciences reference to the literature is much more difficult. There seems to be no reason why an interchange of abstracts between different countries could not be arranged, and, indeed, it might be the best method of obtaining abstracts to have the author of a paper supply an abstract suitable in form and length for the abstract journal at the same time that he sends his paper to the journal which publishes it.

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[2] "The Organisation of Industrial Scientific Research," *Science*, 1916 p. 763 NATURE, 1916 pp. 411 and 431.

(3) *The Utilisation of Scientific Knowledge.*

The actual application of science to industry is so vast a subject that it cannot be considered here, but it is not satisfactory to leave the results of research at the point where they are published in papers and filed in the abstract journals. In order to make them available as a part of scientific knowledge the new information as it is obtained must be incorporated in books.

There are three classes of books dealing with scientific work, which require separate consideration. The first class comprises the dictionaries, in which almost all the progress in some branches of science can conveniently be summarised. Beilstein's "Dictionary of Organic Chemistry" is a good example of the way in which almost all the facts of a science can be absorbed in a classified form and made available for ready reference. These dictionaries, in fact, represent the critical and discriminating summary of the scientific publications on the subjects with which they deal, and the preparation of such dictionaries should be ensured by international co-operation of the national societies.

Other sciences, however, do not by their nature lend themselves to the convenient preparation of dictionaries, and what is wanted in this case are critical and well-arranged handbooks covering the whole science, and resuming impartially, but critically, the various additions which are made from time to time in the different branches of the subject. These handbooks, as well as the dictionaries, would, of course, require the addition of supplementary volumes from time to time, and occasional complete revision.

The preparation of both dictionaries and handbooks would, of course, be greatly facilitated by the existence of a numerically classified card index to the literature concerned, and the preparation and revision of such books might well be undertaken in connection with the large libraries having in their possession the complete classified card indexes.

On the other hand, for the assistance of advanced students of science, what is required is a steady supply of monographs correlating critically and comprehensively all the literature in a special field, and these must be brought up to date from time to time. Such monographs are especially required in connection with rapidly developing new branches of science; it is difficult to over-estimate the importance and value for progress in research of such a book as Bragg's "X-rays and Crystal Structure," for instance, and while nothing should be done to hinder individual initiative in publishing such books, it would seem that when it was apparent that some branch of science required such a monograph a national society might very well approach well-known workers in the field and request them to write such a book, offering its assistance in the matter of bibliography, and also offering to arrange for the publication of the manuscript.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

THE Science Museum, South Kensington, was reopened to the public on Tuesday, January 1. The museum has been closed to the public for nearly two years; it has, however, been open without interruption for students. As compared with 1914 conditions, the extent and the hours of opening for 1918 are somewhat reduced, but the greater part of the museum will be open free on every weekday from 10 a.m. to 5 p.m., and on Sundays from 2.30 p.m. to 5 p.m. The collections contain many unique objects of great interest as representing discoveries, inventions, and appliances that have been of first-rate importance in the advancement of science and of industry. Such objects as Watt's engines, early locomotives, steamships, flying machines, reaping machines, and textile machinery are records of British contributions to the progress of the world; and it is gratifying that these can again be made available for inspection by visitors to London from all parts of the United Kingdom and from distant parts of the Empire.

A COPY of the calendar for the session 1917–18 of the University of Sheffield has been received. In addition to the courses of study arranged for students preparing for graduation in the ordinary university faculties, many other departments, designed to meet the more special needs of the area served by the University, have been inaugurated. Among these may be mentioned the two years' course of work in the University and the Sheffield Training College of Domestic Science; lectures on welfare work for men and women; and an extensive system of University extension work. The departments of applied science are intimately associated with local industries. The faculty of engineering, for instance, includes departments of mechanical, electrical, civil, mining, and chemical engineering, applied chemistry, building, and glass technology. The faculty of metallurgy is concerned with ferrous and non-ferrous metallurgy. The diplomas and certificates of the University are recognised as exempting from examinations for admission to many professional institutions; and the University has, also, been recognised by the Home Office as an approved institution for the examination of mine surveyors. A research delegacy in glass technology, consisting partly of members of the University and partly of representatives of the glass industry, has been instituted. The aims of the delegacy are to promote research in glass technology and to provide for the teaching and training of students in this subject.

AN interesting account was published in the *Times* of December 29 of "Khaki College," a school of civil learning which has been inaugurated in a division of the Canadian Army stationed at Witley Camp in Surrey. Khaki College is the expression of the spirit and ideal of a young and vigorous Oversea nation; and its most important aim is to help young soldiers, whose studies may have been interrupted by the war, still to equip themselves for the return to civil life. At a camp there is little for the men to do in the evenings, and those responsible for providing healthy recreation for the Canadian soldiers organised regular meetings of men under a tree in the "Pine Grove" to discuss questions of academic interest, and to listen to lectures by officers in command. Soon a demand arose for regular classes, and the would-be students were so many that the authorities of the Canadian Army decided to organise Khaki College. The teaching staffs are recruited from within the Canadian Army, and consist of university professors and others. The courses of lectures cover classics history, modern languages and literatures, mathematics and engineer-